PART 1

INTRODUCTION

Chapter 4. Representativeness of the LMMBP Years Relative to Lake Michigan's Historic Record

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1.4.1 Introduction

A major concern related to modeling contaminants in the lake was the representativeness of the years of sampling (1994-1995) relative to the historical record. This was particularly important when using the models to predict future conditions in the lake. The models were calibrated using 1994-1995 data collected during the project. If these data did not represent something close to average conditions, the resulting predictions could be biased. Parameters considered most important to the performance of the models included ice cover, air temperature, water temperature, lake water levels, precipitation, tributary flows, and wave heights. Each of these were investigated for the representativeness of the 1994-1995 project data relative to the available historical data record.

1.4.2 Ice Cover

Ice cover impacts the volatilization, absorption, and physical mixing of the lake during the winter months. In locations where there is ice cover, gas exchange between the water and atmosphere is prevented by the physical barrier. Physical mixing includes not only the mixing of the water column but also the interaction of waves with the lake bottom to resuspend sediments. Winters having extensive ice cover yield a more poorly mixed water column, and a large region of the lake becomes depositional due to lack of wave resuspension of sediments. Once ice retreats in the spring, sediments accumulated during ice cover will be resuspended as a pulse. Ice cover can cause significant changes in winter circulation patterns in a large lake (Campbell *et al.*, 1987). The years of interest that were important were 1982, 1983, 1994, and 1995. The hydrodynamic modeling included three-dimensional lake circulation, surface flux for atmospheric input, and wind-wave models (Schwab and Beletsky, 1998). These were calibrated for the period of 1982-1983 using temperature, current, water level, and wind-wave measurements. The calibrated model was applied to 1994-1995 and validated. There was no ice modeling component for the version of hydrodynamic model applied. Thus, ice cover was important for understanding any potential weakness associated with the hydrodynamic results as well as the dynamics of exchanges between the water and the atmosphere.

Ice cover data were available from the National Oceanic and Atmospheric Administration (NOAA)/ Great Lakes Environmental Research Laboratory (GLERL) (Assel, 2003). This data set is partially described in Assel *et al*. (2002). Tabular information presented in Assel (2003) were summarized in a manner that seemed appropriate for this discussion (Table 1.4.1). For the period when ice was recorded on Lake Michigan, the mean and median daily ice cover were 16.7% and 14.7%, respectively. Ice years began with the first ice. For example, 1982 may include December of 1981. Both 1982 and 1994 were greater than the mean and median; whereas, 1983 and 1995 were less than the mean and median. None of the four years represented an extreme of mean daily ice cover. The lowest ice cover was observed in 2002, and the highest was observed in 1977. Results for each winter's maximum daily ice cover were similar to mean daily ice cover. None of the four years represented an extreme of maximum daily ice cover. As before, 1982 and 1994 were above the mean and median, and 1983 and 1995 were below the mean and median. The maximum mean occurred in 1977, and the minimum mean occurred in 2002. For all four years, 1982 and 1994 were above average for number of days ice was observed, and 1983 and 1984 were slightly below the average. None of the four years represented a minimum or maximum extreme. Ice cover is extremely variable from year-to-year. The impact upon hydrodynamics as modeled was believed to be minimal with respect to 1983 and 1995 when ice cover was quite low. Though high ice cover occurred during the winters of 1982 and 1994, these periods were not a part of the hydrodynamic model period. Using the hydrodynamic model information for models that are used to predict future conditions could lead to potential errors. Modeled circulation patterns could be in error and impact a high bias to modeled current velocities during the winters of high ice cover years due to the lack of an ice model within the hydrodynamics model.

1.4.3 Water and Air Temperatures

Water and air temperature data were retrieved from the National Data Buoy Center (U.S. Department of Commerce, 2002). The buoy numbers are 45002 (north buoy) and 45007 (south buoy) (Figure 1.4.1). Water temperature sensors were located 1 m below the water surface, and air temperature sensors were located 4 m above the surface. Water and air temperature data were available 1979 through 2002 for the north buoy and 1981 through 2002 for the south buoy.

Water temperature is highly variable from year-to-year. The data had been stratified in two ways for presentation. First, monthly mean temperatures were calculated and plotted for the south (Figure 1.4.2) and north (Figure 1.4.3) buoys. Years of importance to the hydrodynamic model were highlighted. It was interesting to note that 1983 and

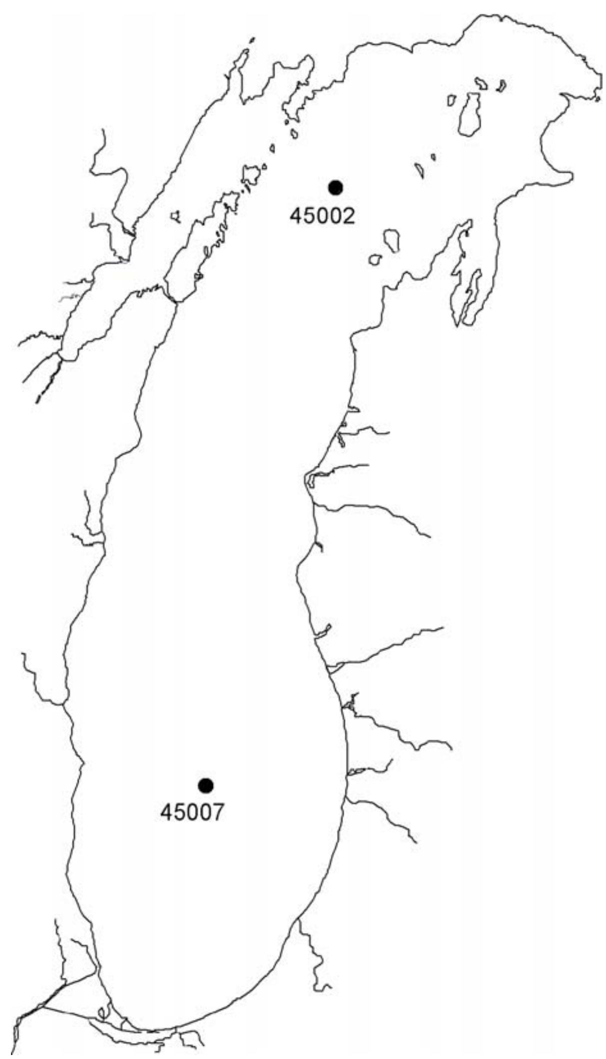

Figure 1.4.1. Location of the NOAA's buoys in Lake Michigan.

Table 1.4.1. Summary of Lake Michigan Ice Cover Based Upon Assel (2003)

Year	Mean Daily Ice Cover During Ice Period	Days of Observed Ice	Maximum Daily Ice Cover
1973	13.3	104	33.0
1974	16.9	122	39.4
1975	13.9	113	28.1
1976	15.5	119	29.5
1977	46.5	132	93.1
1978	26.6	132	66.6
1979	35.2	132	92.3
1980	18.2	106	38.6
1981	24.6	112	53.8
1982	24.0	135	60.2
1983	8.2	118	23.6
1984	15.6	127	43.3
1985	20.1	119	41.3
1986	25.3	126	66.8
1987	9.1	100	19.3
1988	16.6	104	32.7
1989	13.1	140	30.9
1990	17.5	132	32.4
1991	10.0	120	21.5
1992	8.3	149	32.8
1993	11.0	126	32.2
1994	27.3	134	82.7
1995	7.2	120	21.6
1996	19.4	161	75.0
1997	13.4	156	37.8
1998	6.1	109	15.1
1999	8.7	111	23.0
2000	9.2	103	27.2
2001	13.4	134	29.5
2002	6.0	116	12.4
Mean	16.7	124	41.2
Median	14.7	121	32.8
Minimum	6.0	100	12.4
Maximum	46.5	161	93.1

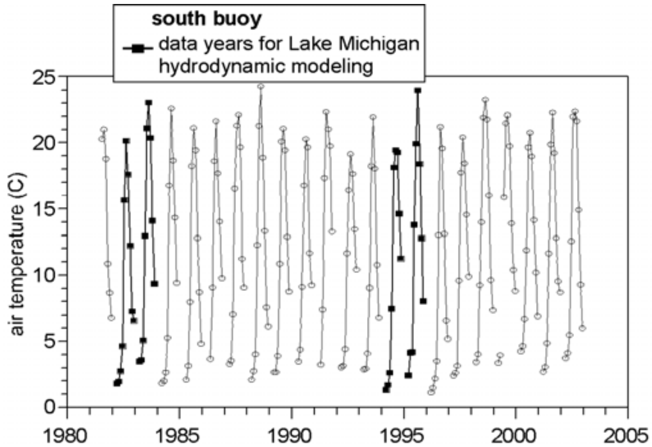

Figure 1.4.2. Monthly mean water temperatures in southern Lake Michigan.

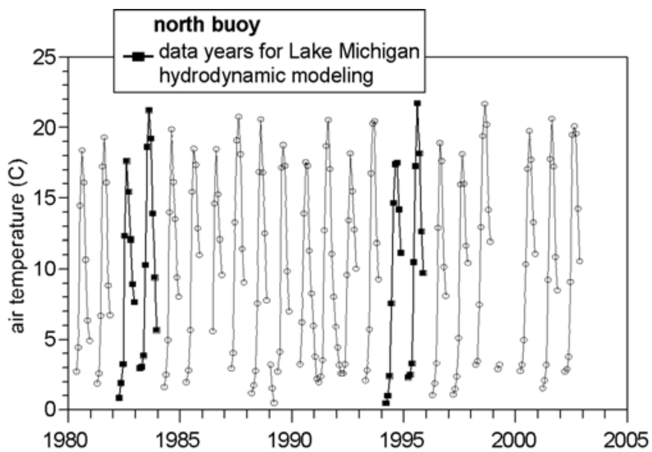

Figure 1.4.3. Monthly mean water temperatures in northern Lake Michigan.

1995 had higher monthly mean temperatures than 1982 or 1994. Both 1983 and 1995 had above normal maximum mean monthly temperature; whereas, 1982 had a typical maximum and 1995 had a very low maximum. This was reflected in the previously discussed ice cover for the four years. Water temperatures tended to be higher at the southern buoy than at the northern buoy, reflecting its more southerly latitude.

The rate at which the lake warms each year is important for the eutrophication and polychlorinated biphenyl (PCB) models. A more rapid warming resulted in an earlier spring diatom bloom when preferred water temperatures were reached. This impacted the timing of annual events, including generation of biotic carbon to which PCBs partition. One way to identify the relative warming rate among years was to look at the mean June water temperature for the period of observation available from the NOAA buoys. Mean June temperatures at the south (Figure 1.4.4) and north (Figure 1.4.5) showed similar patterns that were quite interesting. Beginning in 1983, relatively high mean June temperatures were observed every four years (1983, 1987, 1991, 1995, 1999). This cycling, as well as the apparent increasing mean June water temperature for the period of record, should be further investigated. Both these trends can impact long-term model forecasts. The years of the Lake Michigan Mass Balance Project (LMMBP) (1994 and 1995) represented a fairly average mean June temperature and one of the relatively high means, respectively.

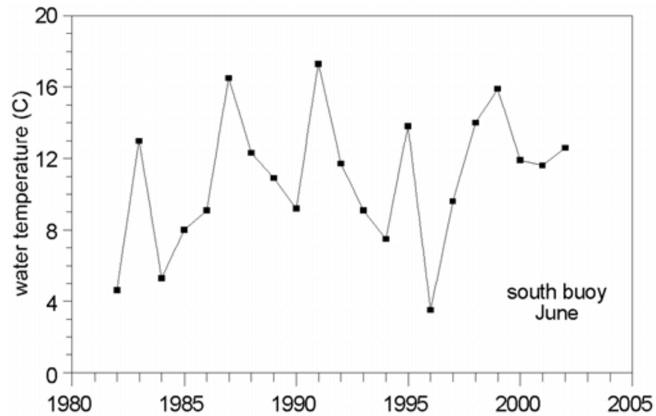

Figure 1.4.4. Mean June water temperatures in southern Lake Michigan.

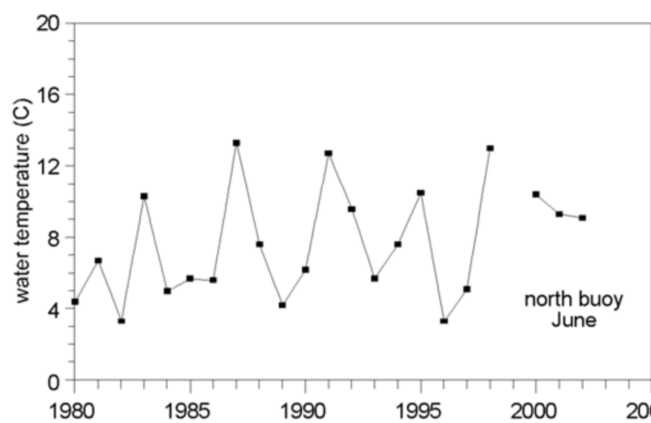

Figure 1.4.5. Mean June water temperatures in northern Lake Michigan.

This, in part, explained why sampling missed the spring 1995 diatom bloom.

The exchange of PCBs between the air and water were dependent on both water and air temperatures. Air temperature varied from year-to-year at the south and north buoys (Figure 1.4.6 and 1.4.7). Because air temperature drives observed water temperature, it was not surprising that patterns observed and conclusions made for water temperature are the same for air temperature. The cyclic pattern of June mean water temperatures was also found for the air temperatures (Figures 1.4.8 and 1.4.9). As additional data become available, future modeling efforts will need to address these cyclic patterns and long-term temperature trends for water and air temperatures.

1.4.4 Lake Water Levels

Lake levels can affect model geometry. If segment volume deviates significantly from the volumes used at the time of calibration, model results can be impacted. On a percentage basis, the impact will be most noticeable for shallow water segments and predictions from the hydrodynamic model and surface water model could be affected. Monthly mean lake water levels varied between 175.5 and 177.5 m for the period of record (1918-1997). Lake levels during 1994 and 1995 were near the average for the period of record (Figure 1.4.10).

1.4.5 Precipitation

Precipitation influences the flux of airborne contaminants to the lake, impacts tributary loading rates, and controls water levels. The 1982 and 1983 hydrodynamic years, and the 1994 and 1995 project years were compared to the previous 50 years of data (Croley and Hunter, 1994).

1.4.5.1 Annual Comparisons

Precipitation to Lake Michigan for 1982, 1983, 1994, 1995 were close to the 50-year mean for the lake (Figure 1.4.11). 1982 and 1983 were slightly above the mean, and 1994 and 1995 were slightly below the mean. 1995 total annual precipitation was very close to the 50-year mean for over-lake precipitation. No visual trend was apparent in the total annual amounts of precipitation over the 50-year period.

1.4.5.2 Monthly Comparisons

The monthly mean precipitation for 1982, 1983, 1994, and 1995 were compared to the 50-year mean for the period of 1949 through 1998 (Figure 1.4.12). For the years of interest, January, July, November and December of 1982; May of 1983; and October of 1995 had relative high amounts of precipitation, exceeding one standard deviation of the 50-year mean. For the four years of interest, February of 1982; June of 1983; March, May and December of 1994; and June of 1995 had relatively low amounts of precipitation. This illustrates that, in any one year, precipitation varies from month-to-month while the precipitation for the year can be at or near the average expected.

1.4.6 Tributary Flows

Tributary flows impact the delivery of materials to the lake, including nutrients and contaminants. During high flow events triggered by spring snow melt or rain events, tributary flows increase and materials can be carried from the watersheds to the tributaries. Within the tributary, sediments containing contaminants may resuspend. Thus, the fluxes of solids, nutrients, and contaminants to the lake have the potential to increase during high flow events. Tributary flows were obtained from the United States Geological Survey (USGS) website (www.usgs.gov). A historical average and median daily flow were calculated for each tributary for the period of record, as well as for the 1994-1995 and 1982-1983 time periods. During 1982 and 1983, tributary flows were approximately 20% greater than the average flows (Figure 1.4.13). The 1994-1995 time period had relatively ordinary tributary flows (Figure 1.4.14).

1.4.7 Wave Heights

In Lake Michigan, waves are the driving force for the resuspension of sediments and their associated contaminants. As waves move from offshore to inshore, they begin to interact with the lake bottom. The energy associated with the waves serves to resuspend the sediments. Lake Michigan is deep enough such that it can be divided into three zones based upon the potential for waves to resuspend sediments. The zones are non-depositional,

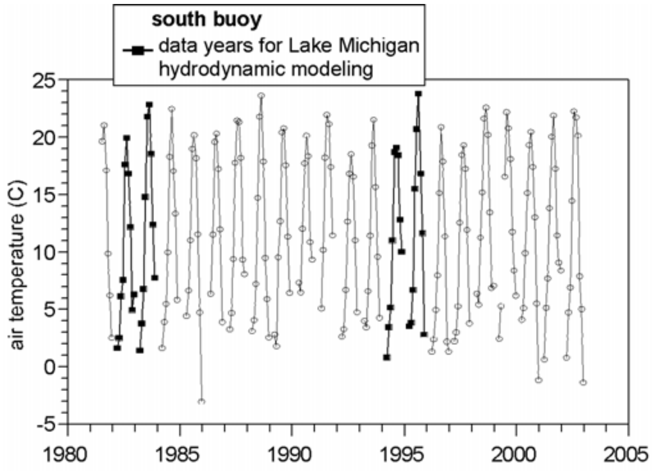

Figure 1.4.6. Monthly mean air temperatures in southern Lake Michigan.

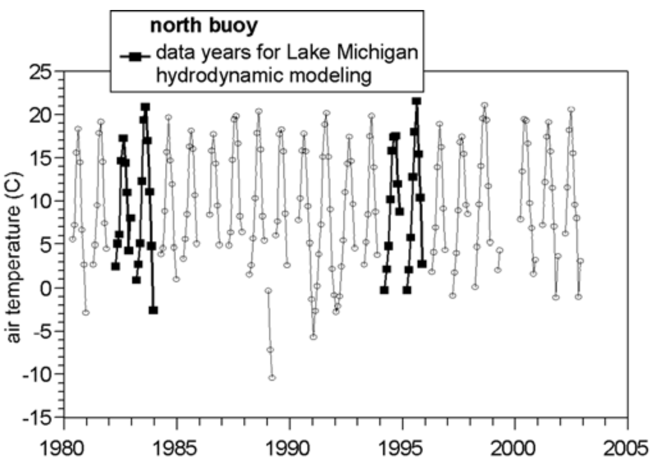

Figure 1.4.7. Monthly mean air temperatures in northern Lake Michigan.

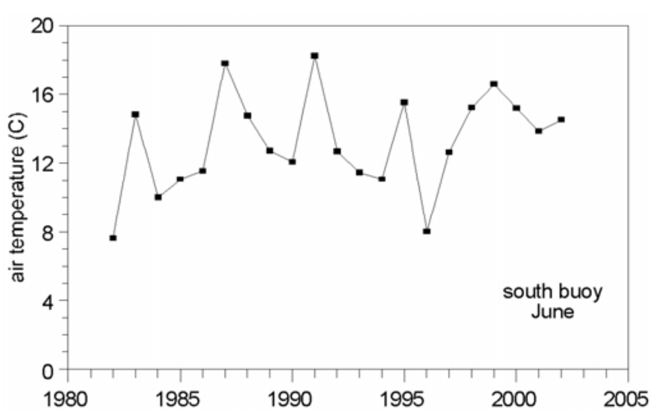

Figure 1.4.8. Mean June air temperatures in southern Lake Michigan.

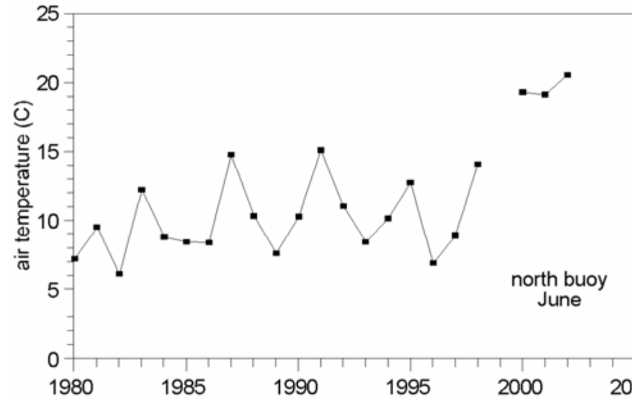

Figure 1.4.9. Mean June air temperatures in northern Lake Michigan.

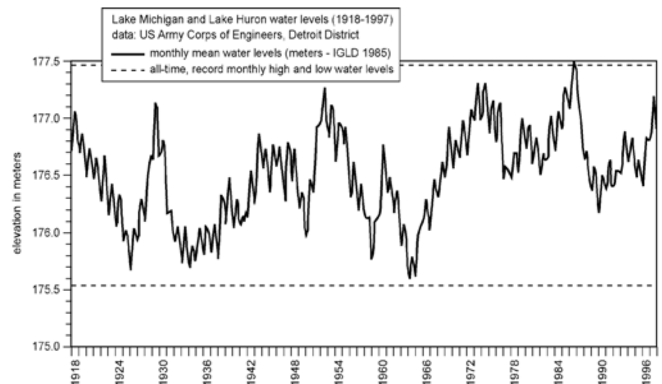

Figure 1.4.10. Record of mean monthly water levels for Lake Michigan.

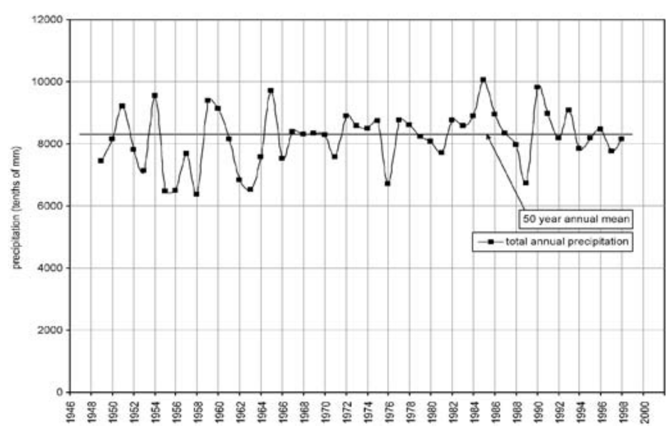

Figure 1.4.11. Annual precipitation to Lake Michigan between 1949 and 1998.

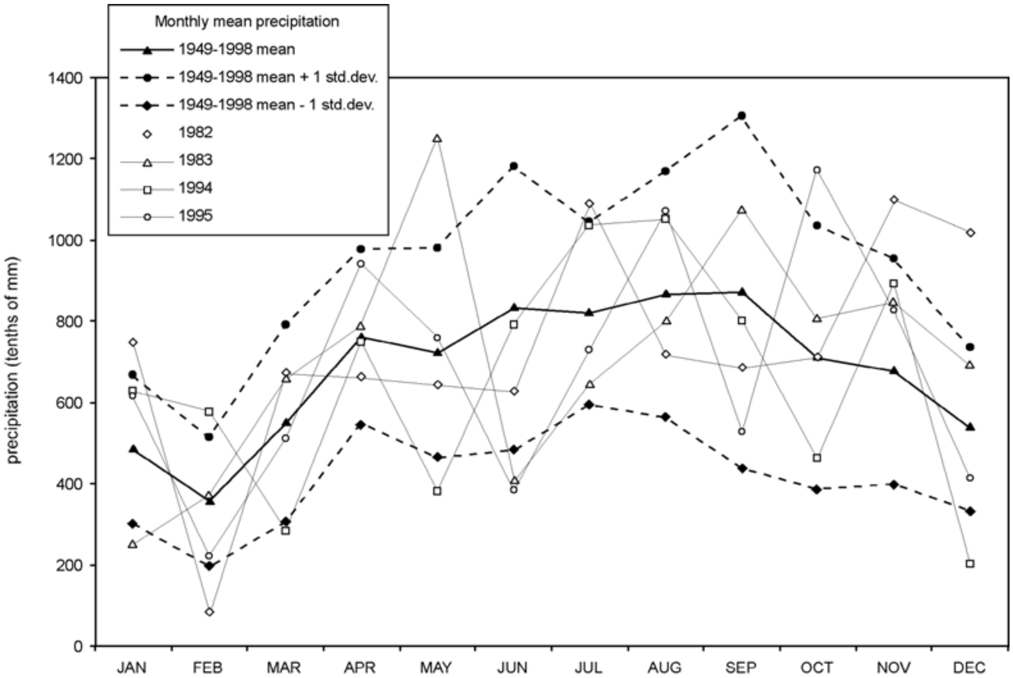

Figure 1.4.12. Comparison of 1982, 1983, 1994, and 1995 monthly mean precipitation to the means for the period of 1949 through 1998.

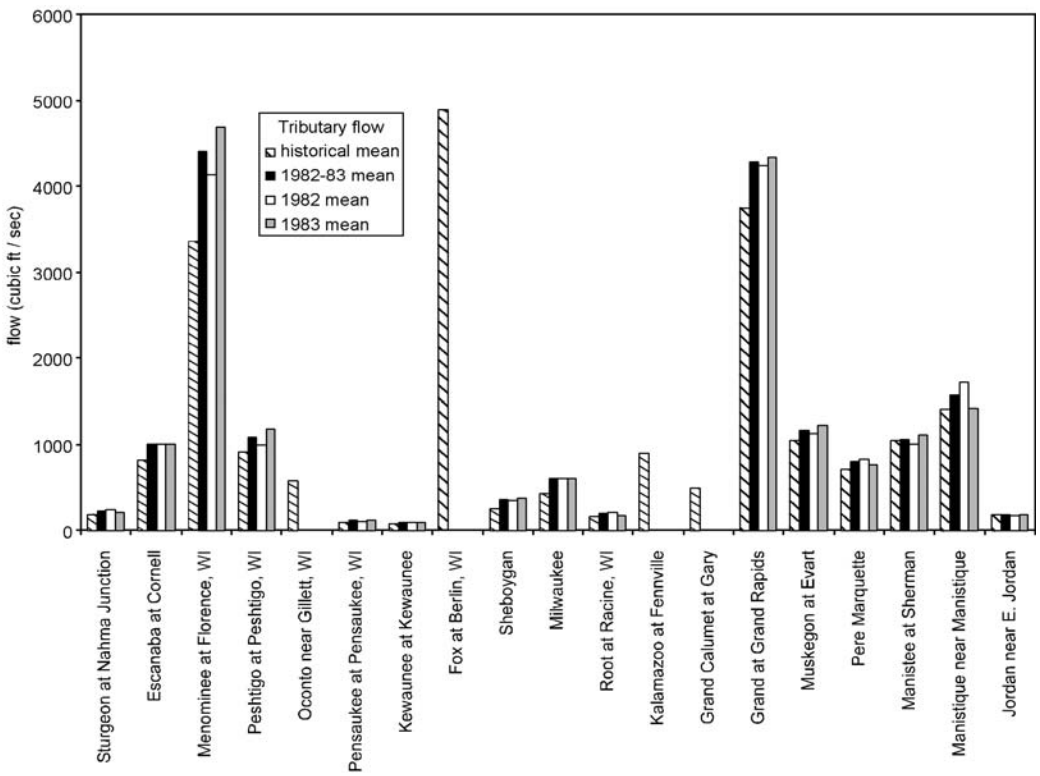

Figure 1.4.13. Comparison of tributary flow for hydrodynamic model calibration (1982-1983) to the historic means.

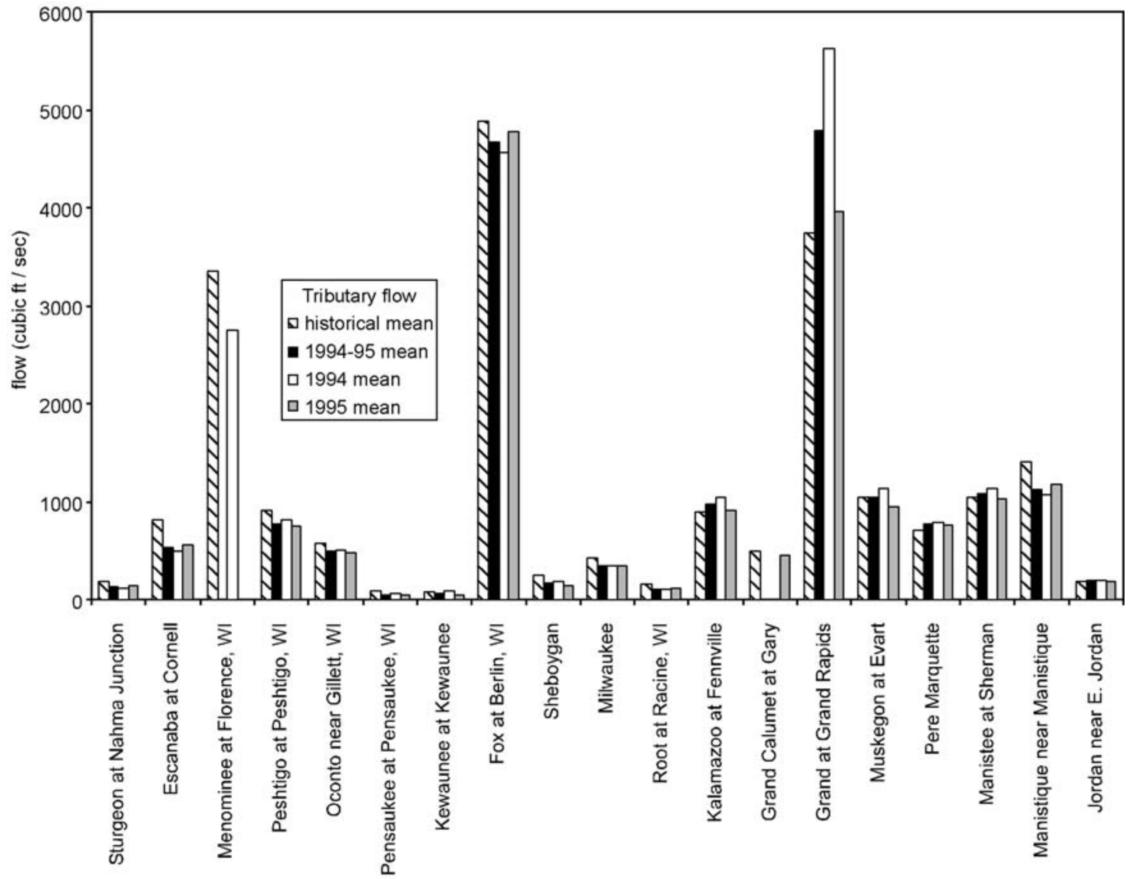

Figure 1.4.14. Comparison of tributary flow for the study period (1994-1995) to the historic means.

transitional, and depositional. The definitions of these zones were based on deep-water wave data.

The complete records of NOAA buoy data for Lake Michigan at the northern buoy (45002) and southern buoy (45007) were assessed to determine the representativeness of the 1994-1995 wave data relative to the period of record (U.S. Department of Commerce, 2002). For 45002, the record began in 1979; whereas, the 45007 record began in 1981. These data were chosen because they are the most complete data sets for Lake Michigan deep-water waves. Determining the representativeness of one period of time relative to the entire record can be very complex and can lead to mixed conclusions. The entire period of record from each buoy was examined with respect to wave height, maximum wave height in any one year, the water depth at which waves begin to interact with the lake bottom, and the horizontal component of the wave's orbital velocity. Some of these were done with respect to the mean and median. Velocity and water depth of interaction with the lake bottom were calculated on the basis of deep-water linear wave theory (Sverdrup *et al.*, 1942).

$$L = gT^2/2\pi \qquad (1.4.1)$$

where,

L = wave length, cm

T = wave period, s

g = acceleration due to gravity, cm/s^2

The water depth at which a wave begins to interact with the lake bottom (d) is equal to one-half the calculated wave length (L) (Sverdrup *et al.*, 1942).

The maximum horizontal component of a wave's orbital velocity (μ_{max}) was calculated with the following equation (U.S. Army Coastal Engineering Research Center, 1973).

$$\mu_{max} = \frac{H\sqrt{gd}}{2\,\pi\,L} \qquad (1.4.2)$$

where,

H = wave height, cm

For both 1994 and 1995, mean wave heights at the northern and southern buoys were similar to historic mean and median observations (Table 1.4.2). Maximum wave heights for these years were high at the northern buoy relative to the historical mean and median heights for both years; however, they were less than the historical maximum wave height at both locations. At the southern buoy, maximum wave heights were high in 1982, 1983, and 1995 relative to historic mean and median maximum heights. At this location, the 1994 maximum height was lower than historic means and medians. For all calibration and study years, the maximum wave heights were neither an extreme high or low for the period of observation at the two locations.

At both buoys, the annual maximum water depths of wave interaction with sediments were not unusual. Though at the maximum in the southern basin (78 m), the maximum was achieved for more than one-half the years of record (Table 1.4.2).

During the calibration and study years, the annual maximum horizontal component of wave orbital velocity ranged between 11.2 and 15.0 cm/s (Table 1.4.2). These observations were close to their historical means. Chambers and Eadie (1981) hypothesized that thermal bar migration generated currents of four to 13.4 cm/s which were enough to resuspend surficial shelf sediment. For fine/medium sand in southwestern Lake Michigan, a near-bottom wave orbital velocity of 17.8 cm/s was enough to initiate resuspension (Lesht, 1989). Similar results (18 cm/s) were found for silty sand in southeastern Lake Michigan (Lesht and Hawley 1987). Sediment resuspension was found in Hamilton Harbor at bottom current speeds of 4.8 cm/s (Brassard and Morris, 1997). Thus the annual maximum horizontal component of wave orbital velocity was sufficient to at least once, on an annual basis, resuspend fine-grained (silt and clay) sediment.

Therefore, it appeared that the repetitious use of the 1994 through 1995 Princeton Ocean Model (POM) results will not introduce bias to the results. Though 1994 and 1995 were not the perfect mean and median situation, they were not singular extremes of what has historically occurred within the lake.

1.4.8 Summary

Lake Michigan is acted upon by a number of physical parameters that impact the physics, chemistry, and biology of the lake. For a lake the size of Lake Michigan, changes in these parameters can lead to significant changes, especially when models are used in long-term predictions to predict the outcome of various scenarios. The primary driving forces are wind, air temperature, and precipitation. These impact tributary flows, lake levels, waves, water circulation, water temperature, and ice cover. For the period of record, these driving forces varied from year-to-year. The period of 1982 to 1983 was used to calibrate the hydrodynamic models. Fortunately for the period of time the models were calibrated, conditions were not at any extreme. This was also true for the period of 1994 and 1995 when the models were applied. However, the impact of ice cover remains a concern and will have to be dealt with in the future.

Temperature can impact atrazine modeling. Air temperature impacts how quickly the lake warms in any one year. Water temperature impacts the volatilization of atrazine. There appears to be a four-year cycle of quicker warming which exists within a trend of general warming of the lake. The trend of warming may be part of a longer term undocumented cycle or may be related to climate change. For future modeling, these cycles and trends will have to be considered to improve long-term predictions.

Precipitation will impact both lake levels and tributary flows. Tributary flows have an impact on the delivery of contaminants to the lake. Precipitation was within the normal range for all years of modeling interest, resulting in lake levels and tributary flows that were within normal bounds. Changes in lake levels as well as the response of tributaries to precipitation events will need to be considered for future modeling used to predict changes of contaminants within the lake.

Table 1.4.2. Descriptive Wave Statistics for POM Calibration Years (1982-1983) and Study Years (1994-1995) Compared to the Period of Record for NOAA's Buoys in Northern and Southern Lake Michigan

Description	Historical Mean	Historical Median	Historical Minimum (Year)	Historical Maximum (Year)	1982	1983	1994	1995
Northern Buoy								
Annual Maximum Wave Height, m	4.3	4.1	3.1 (1996)	5.9 (1991)	4.0	4.5	4.6	5.3
Wave Height, m	0.7	0.6	0.6 (numerous)	0.9 (several)	0.8 (Mean)	0.9 (Mean)	0.6 (Mean)	0.7 (Mean)
Annual Maximum Water Depth of Wave Interaction with Bottom Sediments, m	14.1	65		96 (1991)	65	78	78	78
Annual Horizontal Component of Maximum Orbital Wave Velocity, cm/s	4.9	13.4		18.0 (1984)	12.1	11.3	12.7	15.0
Southern Buoy								
Annual Maximum Wave Height, m	4.5	4.2	2.8 (1991)	6.2 (1998)	4.9	5.3	3.7	5.2
Wave Height, m	0.6	0.5	0.5 (several)	0.8 (numerous)	0.8 (Mean)	0.8 (Mean)	0.6 (Mean)	0.5 (Mean)
Annual Maximum Water Depth of Wave Interaction with Bottom Sediments, m	12.7	65		78 (numerous)	65	78	65	78
Annual Horizontal Component of Maximum Orbital Wave Velocity, cm/s	4.6	13.6		19.2 (1998)	13.1	15.0	11.2	14.7

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